Experimental study of degradation effect of non-condensable gas on the super-hydrophobic aluminum tube

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1. Introduction

As energy problems become more serious in the world, it is important to improve the plant efficiency, thereby improving the condensation heat transfer performance of the condenser also becomes crucial. The condensation heat transfer performance of the condenser greatly affects not only the efficiency of the condenser but also the efficiency of the entire plant cycle. Also, if cooling is not performed properly, thermal and mechanical stresses accumulate, thereby defects can be occurred. The presence of non-condensable gas(NCG) inside the condenser reduces condensation heat transfer performance, degrades plant efficiency, causes chemical reaction with internal substances, and causes problems such as corrosion.

Donald Othmer[1] conducted the condensation experiment with the presence of NCG for the first time. They set up the copper tube horizontally and supplied coolant into the tube. The results indicated that when the volume fraction of air was 0.5%, the heat transfer efficiency decreases about 50 % compared to no air condition. Kroger and Rohsenow[2] performed the condensation experiment in the presence of NCG, such as argon and helium. This experiment confirmed the effect of NCG on condensation phenomena. The result showed that the effect of molecular diffusion is more dominant on condensation performance than that of thermal diffusion. Ren et al.[3] performed the condensation experiment inside of the horizontal tube with steam-air mixture. In this experiment, NCG fraction and Reynolds number of coolant are the main variables.

In this paper, the experiments of dropwise condensation(DWC) and filmwise condensation(FWC) were conducted on horizontal aluminum tubes to examine the relation between the condensation heat transfer performance and NCG mass fraction. After that condensation heat transfer performance of DWC was compared to the bare aluminum tubs. DWC was induced by Self Assembled Monolayer(SAM) method. The condensation performance was represented by the overall heat transfer coefficient *U*.

2. Methods and Results

2.1 Theoretical Analysis

The condensation heat transfer rate q_c should be calculated by measuring the mass flow rate of condensate to determine *U*. The modified latent heat of vaporization model (2) by Rohsenow[4] was applied to equation (1) which was to calculate q_c. In equation (2), the latent heat of water $C_{p,l}$ was a value at film temperature, and the enthalpy required for vaporization is a value at T_{sat}

$$q_c = \dot{m}_c \Delta h_{fg}^* \quad (1)$$

$$\Delta h_{fg}^* = \Delta h_{fg} + 0.68 C_{p,l}(T_{sat} - T_{surf}) \quad (2)$$

U was defined by dividing q_c by log mean temperature difference of coolant ΔT_{LMTD} and outside area of a tube A_o. U of FWC and DWC would be calculated with this process and compared to each other.

$$U = \frac{q_c}{\Delta T_{LMTD} \cdot A_o} \quad (3)$$

To calculate the mass fraction of NCG, the air and vapor were assumed as the ideal gas in the case. As shown in equation (4), NCG mass fraction was calculated. m_a was the molar mass of air, m_v was that of vapor, P_a was partial pressure of air, and P_v was that of vapor.

$$N = \frac{P_a m_a}{P_v m_v + P_a m_a} \quad (4)$$

2.2 Experimental facility design

The experimental facility is shown in Fig. 1. The stream of coolant from a cooler and steam from a steam generator was opposite. The steam was injected into the chamber and then condensed. The condensate was collected into the drain tank through the condensate receiver tube. The outer diameter of main tubes was 1 inch, and the tube of connected with steam generator was 0.5 inch. The material of all tubes was stainless steel. The chamber, steam generator and cooler were the main parts of the experimental facility. The detailed explanations of each part were as follow.

The K type thermocouple, the pressure transducer, the flow meter and the level gauge were used to collect data. The K type thermocouples were calibrated to ±0.15 °C accuracy. They were installed at the center of the chamber and each of the inlet and outlet of tubes. The pressure transducer, which was to measure the inner pressure of the chamber, measured absolute pressure from 0 to 2.1 bar with ±0.25 % full scale accuracy. The turbine flow meter measured the mass flow rate of coolant. It could measure 10 to 110 LPM with ±1 % full scale accuracy. The steam flow meter measured the mass flow rate of pure steam, and it could measure 4 to 20 kg/hr with ±1 % full scale accuracy

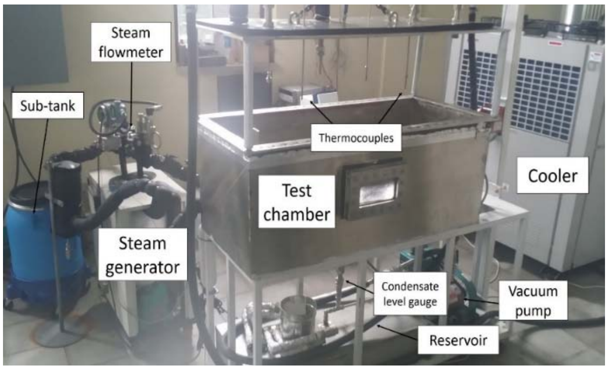

Fig. 1. Manufactured experimental facility.

2.3 Experimental results

The experiment was conducted according to case 1 and 2. The conditions of case 1 was 20 °C coolant inlet temperature and 3.8 kPa P_a. The conditions of case 2 was 20 °C coolant inlet temperature and 6.7 kPa P_a.

The case 1 NCG mass fraction range was from 0.08 to 0.27. Fig. 2 shows U according to NCG mass fraction. Generally, U of the both tubes increased with decreasing NCG, and U of SAM tube was larger than U of bare tube in range higher than 0.09 NCG mass fraction. Under the NCG mass fraction range lower than 0.09, the condensation performance of the SAM tube was failed, that is condensation phenomenon of SAM shown FWC, and its performance was lower than the bare tube. The reason for this fail was that the condensation actively occurred at the SAM tube as increasing the pressure and temperature of the inside steam. When SAM coated tube has been failed, the condensate droplets did not detach from the surface. Furthermore, after the SAM coat degraded, it didn't return to normal until SAM tube was completely dried.

The experiment for case 2 condition was conducted with 0.14 to 0.45 NCG mass fraction range. Fig. 3 shows the result of case 2. Generally, U of the both tube increased with decreasing NCG, but condensation performance degradation was observed at 0.14 NCG mass fraction. The reason for this fail was the same with the case 1 condition.

The important phenomenon in case 2 was that when NCG mass fraction was less than 0.25, the increase rate of U of SAM tube was smaller than when that is larger than 0.25 according to decreasing NCG mass fraction. Observing the surface of SAM tube, flooded condensation phenomenon occurred on SAM tube when NCG mass fraction was 0.25 or less. Milijkovic and Wang [5] briefly explained that flooded condensation is an intermediate condensation phenomenon of the DWC and FWC, and its condensation heat transfer performance is better than FWC, but is worse than perfect DWC. According to this former research, the decreasing of increase rate of U of SAM tube was due to flooded condensation. Flooded condensation was also observed in case 1.

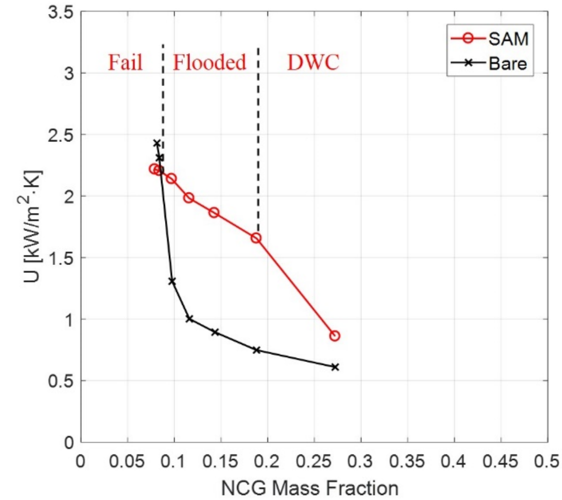

Fig. 2. Overall heat transfer coefficient according to NCG mass fraction in case 1.

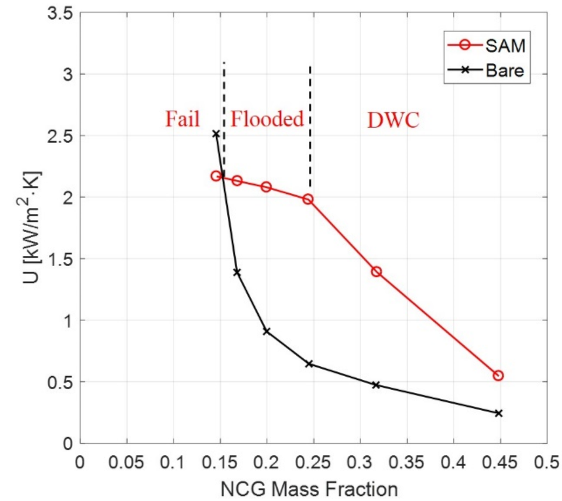

Fig. 3. Overall heat transfer coefficient according to NCG mass fraction in case 2.

3. Conclusions

The presence of NCG inside the condenser reduces condensation heat transfer performance and degrades plant efficiency. To solve these problems, this paper focused on the effects of NCG on DWC and FWC. The experimental facility was designed to observe the condensation phenomenon and performance. Two kind of condenser tubes were used, one was SAM coated aluminum tube to observe DWC, and another was non-coated bare aluminum tube to observe FWC. Through the condensation experiment in various condition, the unique effects of SAM tube on DWC according to NCG mass fraction had been figured out. It is necessary to consider characteristics of SAM coat and controlling the operation condition when applying it to the actual condenser.

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